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Optimal Feeder Reconfiguration with Distributed Generation in Three-Phase Distribution System by Fuzzy Multiobjective and Tabu Search

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1. Introduction

Distribution systems are normally configured radially for effective coordination of their protective devices (Kashem et al., 2006). Two types of switches are generally found in the system for both protection and configuration management. These are sectionalizing switches (normally closed switches) and tie switches (normally opened switches) (Su & Lee, 2003). By changing the status of the sectionalizing and tie switches, the configuration of distribution system is varied and loads are transferred among the feeders while the radial configuration format of electrical supply is still maintained and all load points are not interrupted. This implementation is defined as feeder reconfiguration. The advantages obtained from feeder reconfiguration are, for example, real power loss reduction, balancing system load, bus voltage profile improvement, (Baran & Wu, 1989) increasing system security and reliability, and power quality improvement (Kashem, et al., 2000).

Over the last decade, distribution systems have seen a significant increase in small-scaled generators, which is known as distributed generation (DG). Distributed generators are grid-connected or stand-alone electric generation units located within the distribution system at or near the end user. Recent development in DG technologies such as wind, solar, fuel cells, hydrogen, and biomass has drawn an attention for utilities to accommodate DG units in their systems (Gil & Joos, 2008, Jones & Chowdhury, 2008, Quezada, et al., 2006, Carpaneto, et al., 2006). The introduction of DG units brings a number of technical issues to the system since the distribution network with DG units is no longer passive.

The practical aspects of distribution system should also be considered for the implementation of feeder reconfiguration. The actual distribution feeders are primarily unbalanced in nature due to various reasons, for example, unbalanced consumer loads, presence of single, double, and three-phase line sections, and existence of asymmetrical line sections. The inclusion of system unbalances increases the dimension of the feeder configuration problem because all three phases have to be considered instead of a single phase balanced representation. Consequently, the analysis of distribution systems necessarily required a power flow algorithm with complete three-phase model.

This paper emphasizes on the implementation of feeder reconfiguration to the distribution system with distributed generators. Three objectives to be minimized are real

power loss, feeder load balancing, and number of switching operations of tie and sectionalizing switches. Each objective is modeled by fuzzy set to specify its membership value which represents the satisfaction of the objective. The optimal on/off patterns of the switches that compromise the three objectives while satisfying specified constraints is determined using fuzzy multiobjective and Tabu search algorithm. The effectiveness of the methodology is demonstrated by a practical sized distribution system consisting of 69 bus and 48 load points.

2. Feeder reconfiguration

Feeder Reconfiguration is a very important and usable operation to reduce distribution feeder losses and improve system security. The configuration may be varied via switching operations to transfer loads among the feeders. Two types of switches are used: normally closed switches (sectionalizing switches) and normally open switches (tie switches) (Baran & Wu, 1989). By changing the open/close status of the feeder switches load currents can be transferred from feeder to feeder. During a fault, switches are used to fault isolation and service restoration. There are numerous numbers of switches in the distribution system, and the number of possible switching operations is tremendous. Feeder reconfiguration thus becomes a complex decision-making process for dispatchers to follow. There are a number of closed and normally opened switches in a distribution system. The number of possible switching actions makes feeder reconfiguration become a complex decision-making for system operators. Figure 1 shows a schematic diagram of a simplified primary circuit of a distribution system (Baran & Wu, 1989). In the figure, CB1-CB6 are normally closed switches that connect the line sections, and CB7 is a normally open switch that connects two primary feeders. The two substations can be linked by CB8, while CB9, when closed, will create a loop.

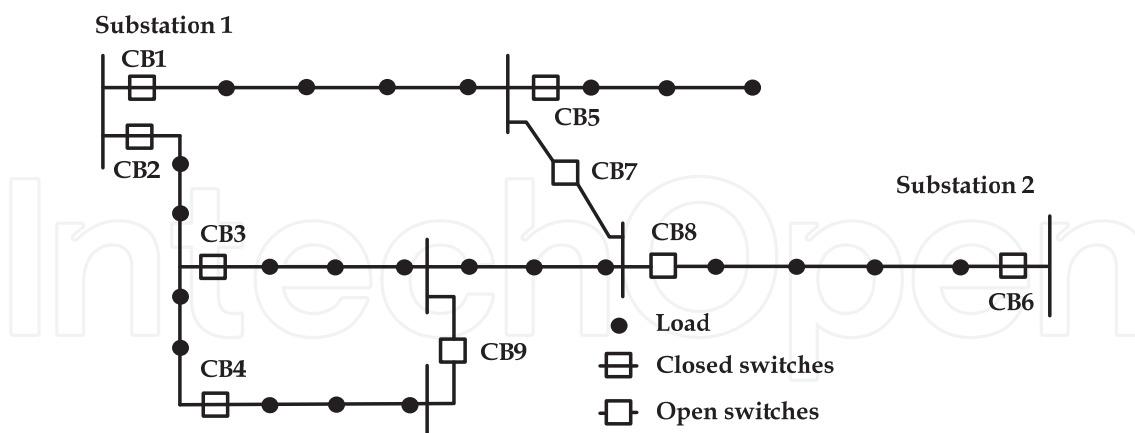


Fig. 1. Schematic diagram of a distribution system

Optimum operation of distribution systems can be achieved by reconfiguring the system to minimize the losses as the operating conditions change. Reconfiguration problem essentially belongs to combinatorial optimization problem because this problem is carried out by taking into account various operational constraints in large scale distribution systems. It is, therefore, difficult to rapidly obtain an exact optimal solution on real system (Chung-Fu, 2008). A flowchart for feeder reconfiguration algorithm is shown in Fig 2.

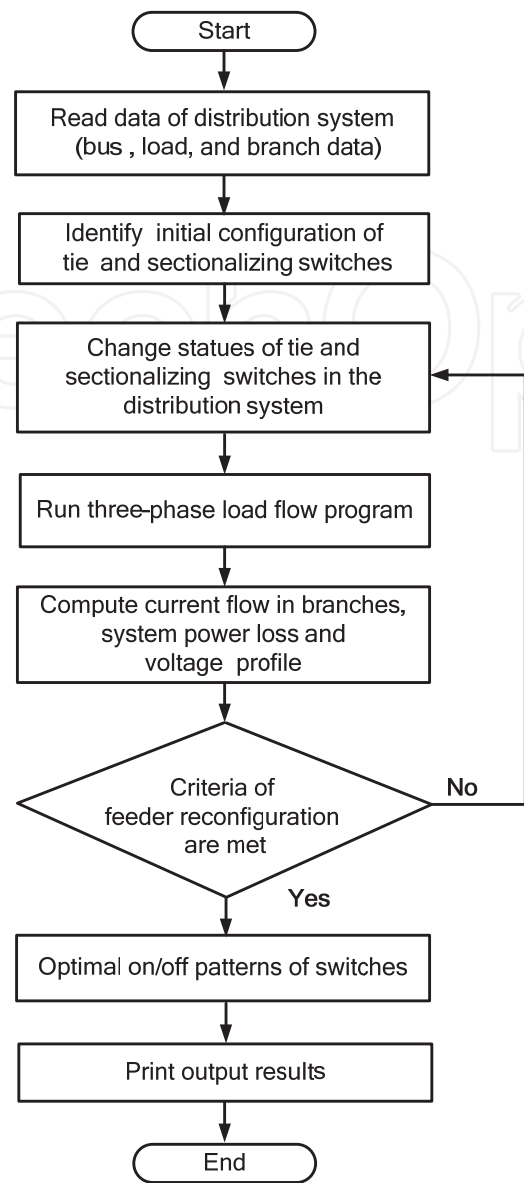


Fig. 2. Flowchart of feeder reconfiguration for loss reduction

3. Tabu search

3.1 Background

Tabu search is a meta-heuristic that guides a local heuristic search strategy to explore the solution space beyond local optimality. Tabu search was developed by Glover and has been used to solve a wide range of hard optimization problems, such as resource planning, telecommunications, financial analysis, scheduling, space planning, and energy distribution (Dengiz & Alabas, 2000). The basic idea behind the search is a move from a current solution to its neighborhood by effectively utilizing a memory to provide an efficient search for optimality. The memory is called “Tabu list”, which stores attributes of solutions. In the search process, the solutions in the Tabu list cannot be a candidate of the next iteration. As a result, it helps inhibit choosing the same solution many times and avoid being trapped into cycling of the solutions (Glover, 1989). The quality of a move in solution space is

assessed by aspiration criteria that provide a mechanism (see Fig. 3) for overriding the Tabu list. Aspiration criteria are analogous to a fitness function of the genetic algorithm and the Boltzman function in the simulated annealing.

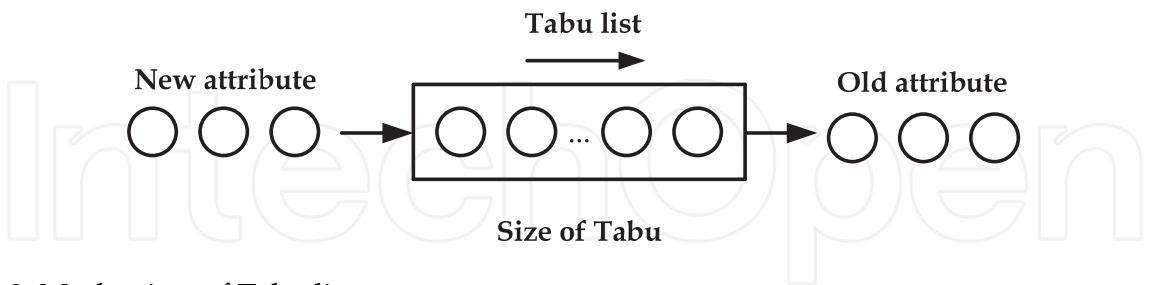


Fig. 3. Mechanism of Tabu list

3.2 Neighborhood

In the search process, a move to the best solution in the neighborhood, although its quality is worse than the current solution, is allowed. This strategy helps escape from local optimal and explore wider in the search space. A Tabu list includes recently selected solutions that are forbidden to prevent cycling. If the move is present in the Tabu list, it is accepted only if it has a better aspiration level than the minimal level so far. Fig. 4 shows the main concept of a search direction in Tabu search (Mori & Ogita, 2002).

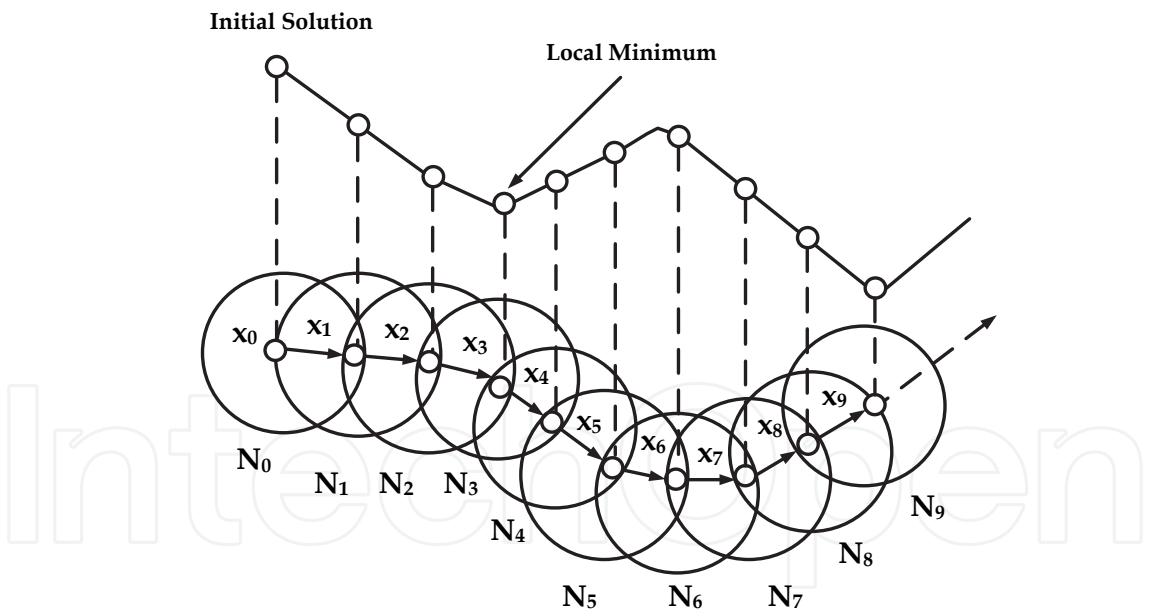


Fig. 4. Search direction of Tabu search

An application of the Tabu search algorithm is shown by a three-feeder distribution system in Fig. 5 (Su, C. T. & Lee, C. S. 2003). The system consists of 16 buses, 13 load points, 13 normally closed switches, and 3 normally open switches. The initial configuration states that switches located on branch No. 14, No. 15 and No. 16 are open. With this configuration, the initial power loss is 511.44 kW. Fig. 6 shows moves from the current solution to two feasible solutions generated by the Tabu search: neighborhood solutions 1 and 2. The moves to solutions 1 and 2 give a power loss of 676.63 kW and 483.87 kW, respectively. The same process

continues until 100 iterations. The optimal solution indicates that switch No. 16 remains open and the statuses of switches No. 7 and 8 are changed from ‘closed’ to ‘open’, giving a real power loss of 466.12 kW.

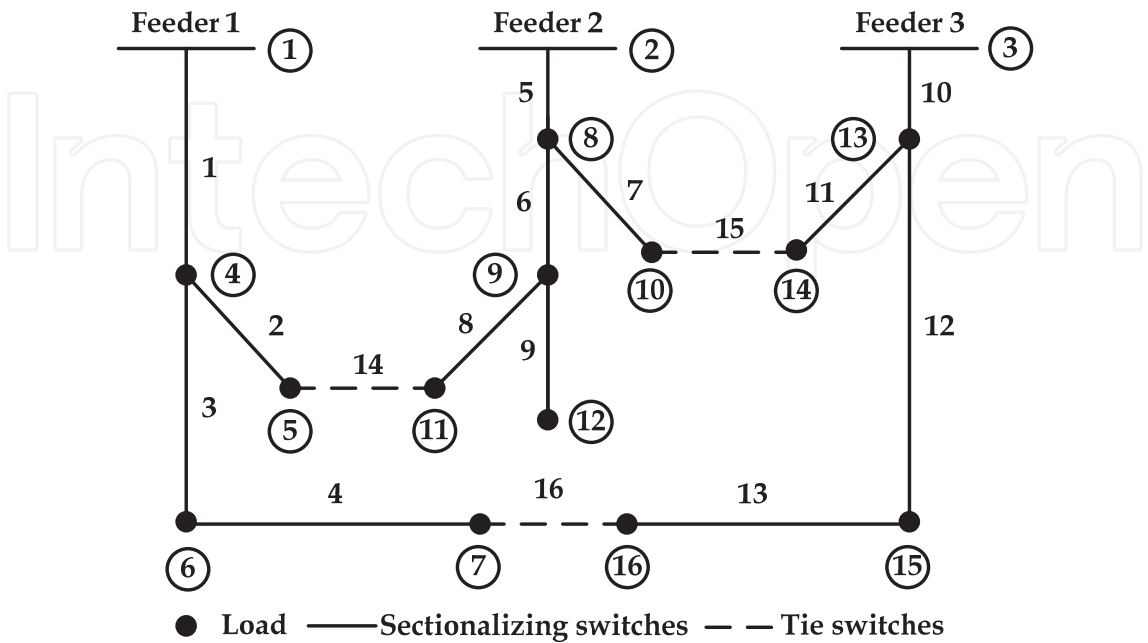


Fig. 5. Single-line diagram of 16-bus distribution system

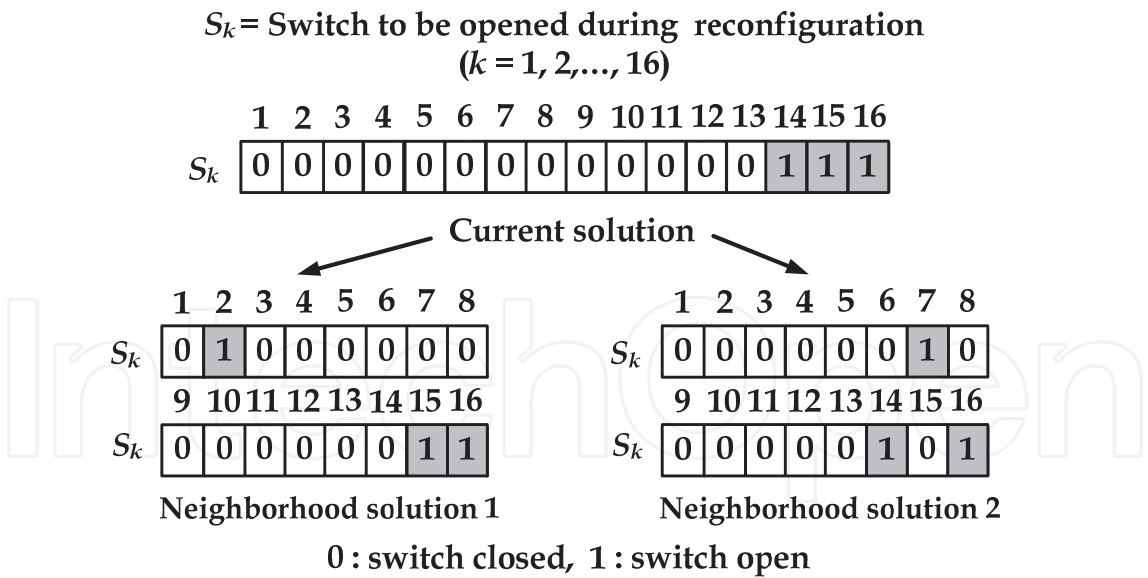


Fig. 6. Neighborhood search for tie and sectionalizing switches

4. Membership function of objective

A. Membership function for power loss

The power loss is calculated by

$$P_{LOSS} = \sum_{k=1}^l |I_k|^2 R_k \tag{1}$$

Where

P_{LOSS} =total power loss

I_k =current flow in branch k

R_k =resistance of branch k

l =number of feeders

Let us define the ratio of power loss as (Das, 2006).

$$PL_t = \frac{P_{LOSS,t}}{P_{LOSS,0}} \tag{2}$$

The membership function of power loss is assigned to be trapezoidal fuzzy number demonstrated in Fig. 7. It is fully satisfied if the system loss is smaller than PL_{min} . Between PL_{min} and PL_{max} , the satisfaction level declines as the system loss becomes wider and unacceptable if exceeding PL_{max} , thus the zero membership value given for this point.

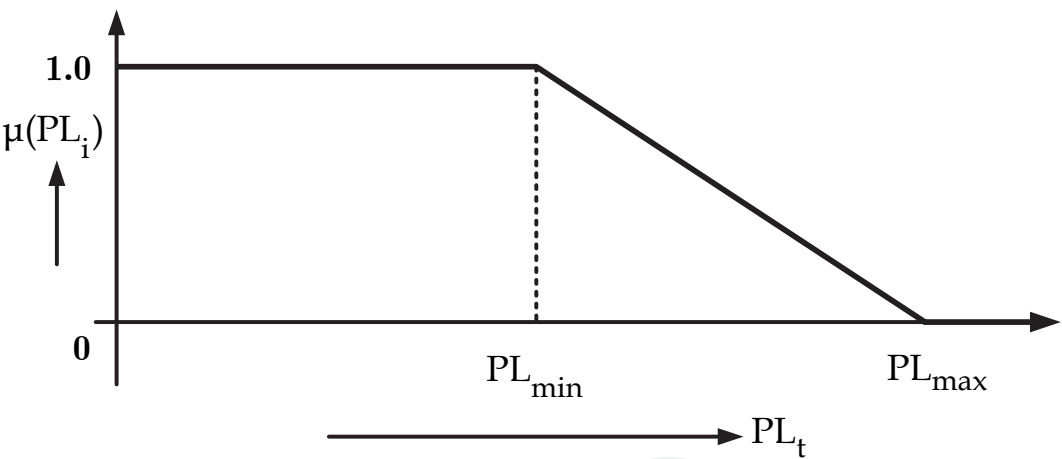


Fig. 7. Membership function for power loss reduction

The membership value $\mu(PL_t)$ derived by this membership function can be written as

$$\mu(PL_t) = \begin{cases} \frac{(PL_{max}-PL_t)}{(PL_{max}-PL_{min})} & \text{for } PL_{min} < PL_t < PL_{max} \\ 1 & \text{for } PL_t \leq PL_{min} \\ 0 & \text{for } PL_t \geq PL_{max} \end{cases} \tag{3}$$

B. Membership function for load balancing

Loading balance index (LBI) represents the degree of loading among feeders. This index measures how much a branch can be loaded without exceeding the rated capacity of the branch indicates (Kashem et al., 2006). LBI may be defined as (Peponis & Papadopoulos, 1995).

$$B_t = \sum_{k \in B} \left(\frac{|I_{k,t}|}{I_k^{\max}} \right)^2 \quad (4)$$

Where

B_t =load balancing index for feeder reconfiguration pattern t

B =set of net work branches forming loops

$I_{k,t}$ =current capability of branch k for feeder reconfiguration pattern t

I_k^{\max} =maximum current capability of branch k

The load balancing index (LBI) in (4) is normalized by

$$LB_t = \frac{B_t}{B_0} \quad (5)$$

Where

LB_t =normalized LBI for feeder reconfiguration pattern t

B_0 =LBI before feeder reconfiguration

The membership function presented in Fig. 8 is used for load balancing objective. As can be seen, the load balancing index is expected to be less than LB_{\min} and not greater than LB_{\max} . Therefore, the allowable range for LB_t varies from 0 to LB_{\max} .

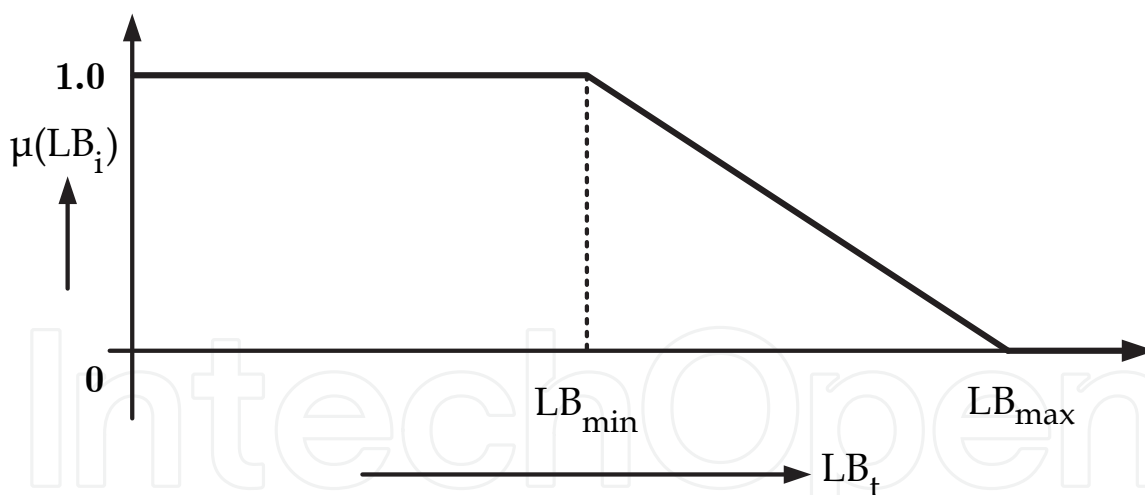


Fig. 8. Membership function for load balancing

LB_t is employed to compute $\mu(LB_t)$ using the membership function given below.

$$\mu(LB_t) = \begin{cases} \frac{(LB_{\max} - LB_t)}{(LB_{\max} - LB_{\min})} & \text{for } LB_{\min} < LB_t < LB_{\max} \\ 1 & \text{for } LB_t \leq LB_{\min} \\ 0 & \text{for } LB_t \geq LB_{\max} \end{cases} \quad (6)$$

C. Membership function for number of switching operations

The membership value for the number of switching operations of sectionalizing and tie switches is represented by Fig. 9. The figure states that as long as the number of switching operations is less than SW_{min} , unity membership value is assigned. The membership function linearly decreases if SW_t lies between SW_{min} and SW_{max} . A zero membership value is assigned to SW_t if it is greater than SW_{max} .

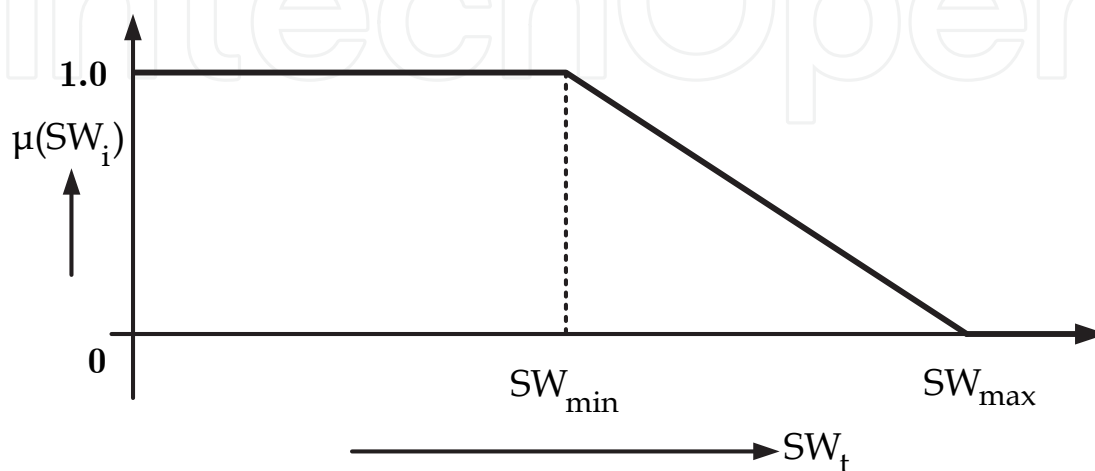


Fig. 9. Membership function for number of switching operation index

The membership function for the number of switching operations is expressed as

$$\mu(SW_t) = \begin{cases} \frac{(SW_{max} - SW_t)}{(SW_{max} - SW_{min})} & \text{for } SW_{min} < SW_t < SW_{max} \\ 1 & \text{for } SW_t \leq SW_{min} \\ 0 & \text{for } SW_t \geq SW_{max} \end{cases} \quad (7)$$

Where

SW_t = switching operation for feeder reconfiguration pattern t

5. Three-phase power flow

Power flow is an essential tool for the steady state operational analysis of power systems. The main objective of power flow analysis is to calculate the real and reactive powers flow in each line as well as the magnitude and phase angle of the voltage at each bus of the system for the specific loading conditions (Subrahmanyam, 2009). Certain applications, particularly in distribution automation and optimization, require repeated power flow solutions. As the power distribution networks become more and more complex, there is a higher demand for efficient and reliable system operation. Consequently, power flow studies must have the capability to handle various system configurations with adequate accuracy and speed.

In general, power systems in steady state analysis are operated with balanced three-phase generation and loads by the transposition of transmission lines. However, it is not always

the case, particularly for radial distribution systems, because of single-phase, two-phase and three-phase loads. As a result, the models based on single phase analysis are not adequate to represent unbalanced three phase networks. The method employed as a major tool to solve the unbalanced power flow problem is based on actual phase quantities with all the relevant equipment modelled in phase coordinates. Thus, power flow solution for unbalanced case and, hence special treatment is required for solving such networks (Ranjan, et. Al., 2004). The equivalent circuit for each line section is represented by the nominal π -equivalent model as shown in Fig. 10, which shows a schematic representation of a line connected between bus i and bus j. This model has one series and two parallel components. The series component stands for the total line impedance consisting of the line resistance and reactance. The parallel components represent the total line capacitance, which is distributed along the line. In the pi-equivalent line representation, the total line capacitance is equally divided into two parts: one lumped at the receiving end bus and the other at sending end bus while the series line impedance is lumped in between. The series impedance and the shunt capacitance for a three-phase line are 3×3 complex matrices which take into account the mutual inductive coupling between the phases (Zimmerman, 1992).

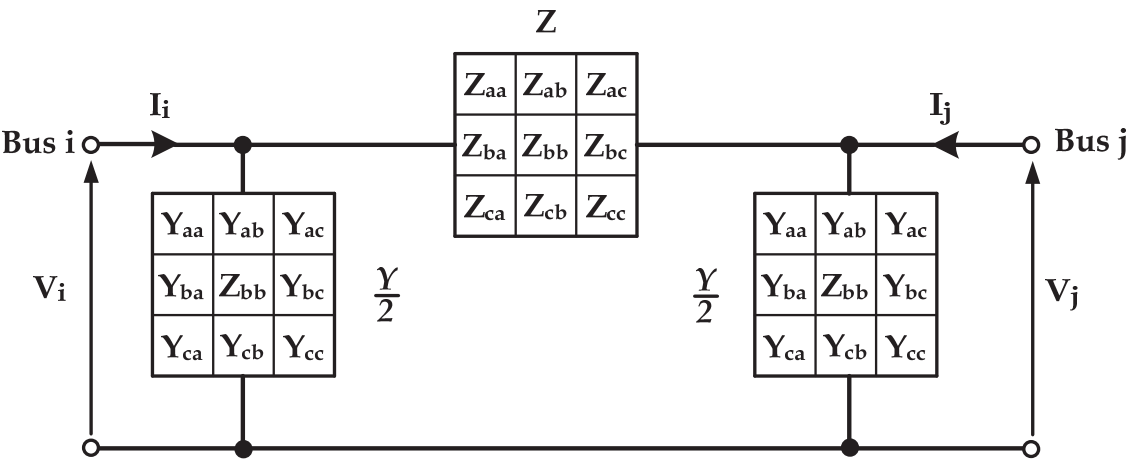


Fig. 10. Compound π -equivalent model for three-phase

If Z and Y are the 3×3 matrices representing the series impedance and shunt admittance, respectively, then the admittance matrix for a three-phase conductor between buses i and j is the 6×6 matrix in equation (8).

$$Y_{ij} = \begin{bmatrix} Z^{-1} + \frac{1}{2}Y & -Z^{-1} \\ -Z^{-1} & Z^{-1} + \frac{1}{2}Y \end{bmatrix} \tag{8}$$

The voltages and currents labeled by the 3×1 vectors V_i, V_j, I_i and I_j in Fig 10. are related by

$$\begin{bmatrix} I_i \\ I_j \end{bmatrix} = Y_{ij} \begin{bmatrix} V_i \\ V_j \end{bmatrix} \tag{9}$$

Given a system with a total of n buses, a bus voltage vector (V_{bus}) and a bus injection current vector (I_{bus}), are defined as

$$V_{\text{bus}} = [V_1^a, V_1^b, V_1^c, V_2^a, V_2^b, V_2^c, \dots, V_n^a, V_n^b, V_n^c]^T \quad (10)$$

$$I_{\text{bus}} = [I_1^a, I_1^b, I_1^c, I_2^a, I_2^b, I_2^c, \dots, I_n^a, I_n^b, I_n^c]^T \quad (11)$$

where V_i^p and I_i^p are complex values representing the voltage and injected current, respectively, of phase p at bus i .

$$I_{\text{bus}} = Y_{\text{bus}} V_{\text{bus}} \quad (12)$$

where $Y_{\text{bus}} = [Y_{ij}^{pm}]$ is a $3n \times 3n$ complex matrix whose element relates the voltage V_j^m to the current I_i^p .

Rewriting (12) as a summation of the individual matrix and vector components gives the injected current of phase p at bus i . Equation (12) thus becomes (13)

$$I_i^p = \sum_{j=1}^n \sum_{m=a}^c Y_{ij}^{pm} V_j^m \quad (13)$$

Active and reactive powers for phase p at bus i presented in terms of the phase voltage magnitudes and angle are described in (14)

$$I_i^p = \sum_{j=1}^n \sum_{m=a}^c Y_{ij}^{pm} V_j^m \quad (14)$$

$$S_i^p = P_i^p + Q_i^p \quad (15)$$

$$P_i^p = |V_i^p| \sum_{j=1}^n \sum_{m=a}^c |V_j^m| [G_{ij}^{pm} \cos \theta_{ij}^{pm} + B_{ij}^{pm} \sin \theta_{ij}^{pm}] \quad (16)$$

$$Q_i^p = |V_i^p| \sum_{j=1}^n \sum_{m=a}^c |V_j^m| [G_{ij}^{pm} \sin \theta_{ij}^{pm} - B_{ij}^{pm} \cos \theta_{ij}^{pm}] \quad (17)$$

Where

p = phases a, b, and c

P_i^p, Q_i^p active and reactive power for phase a, b, and c at bus $i=1,2,3,\dots,n$

$$Y_{ij}^{pm} = G_{ij}^{pm} + jB_{ij}^{pm}$$

V_i^p =voltage for phase a, b, and c of bus i

$$\theta_{ij}^{pm} = \theta_i^p - \theta_j^m$$

6. Problem formulation

The objective functions to be minimized are the system power loss, the load balancing index, and the number of switching operations of sectionalizing and tie switches. Tabu search are employed to generate on/off patterns of the switches. The three objectives of each pattern can then be computed. Each objective is fuzzified using the membership function presented in Section 4. The max-min principle is applied to determine the optimal solution. The objective function can be written as

$$Z = \max\{T_h\} \quad h = 1, 2, 3, \dots, NT \quad (18)$$

$$T_h = \min\{\mu(PL_t), \mu(LB_t), \mu(SW_t)\} \\ \text{for } t = 1, 2, 3, \dots, N_{\text{neighbor}} \quad (19)$$

Where

Z =fuzzy decision for an optimal solution

T_h =fuzzy decision for the objectives being considered

NT =number of solutions in Tabu list

$\mu(PL_t)$ =membership value for power loss of feeder reconfiguration pattern t

$\mu(LB_t)$ =membership value for load balancing of feeder reconfiguration pattern t

$\mu(SW_t)$ =membership value for the number of switching operations of feeder reconfiguration pattern t

N_{neighbor} =number of solutions neighborhood

The objective function is subjected to the following constraints.

1) Power flow equations

2) Bus voltage limits:

$$V_i^{p,\min} \leq V_i^p \leq V_i^{p,\max} \quad (20)$$

3) Feeder capability limits:

$$|I_k^p| \leq I_k^{p,\max} \quad k \in \{1, 2, 3, \dots, l\} \quad (21)$$

4) Radial configuration format

5) No load-point interruption

Where

$V_i^{p,\min}$ $V_i^{p,\max}$ =minimum and maximum voltage for phase a, b, and c

$I_k^{p,\max}$ =maximum current capability for phase a, b, and c of branch k

7. Algorithm by Tabu search

The Tabu search algorithm is applied to solve the optimal or near optimal solution of the feeder configuration problem by taking the following steps:

- Step 1: Read the bus, load and branch data of a distribution system including all the operational constraints.
- Step 2: Randomly select a feasible solution from the search space: $S_0 \in \Omega$, where S_0 is an initial solution and Ω is the search space.
- Step 3: Set the size of a Tabu list, maximum iteration and iteration index $m=1$.
- Step 4: Let the initial solution obtained in step 2 be the current solution and the best solution: $S_{best} = S_0$, and $S_{current} = S_0$, where S_{best} is the best solution in the search space and $S_{current}$ is the current solution in search space.
- Step 5: Perform a power flow analysis to determine power loss, bus voltages, and branch currents.
- Step 6: Determine the membership values of all the objectives.
- Step 7: Calculate $T_h = \min\{\mu(PL_t), \mu(LB_t), \mu(SW_t)\}$. The value of T_h represents the decision in a fuzzy environment that can be viewed as the intersection of the membership functions of objectives (Zimmermann, 1987). The intersection of membership functions is defined by the minimum operation.
- Step 8: Calculate the objective function of S_{best} by $f(S_{best}) = Z = \max\{T_h\}$. The value of Z indicates the highest degree of membership in the fuzzy decision (Zimmermann, 1987) and is assigned to be the aspiration level.
- Step 9: Generate a set of solutions in the neighborhood of $S_{current}$ by changing the switch numbers that should be opened. This set of solutions is designated as $S_{neighbor}$.
- Step 10: Calculate the aspiration level for each member of $S_{neighbor}$ and choose the one that has the highest aspiration level, $S_{neighbor_best}$.
- Step 11: Check whether the attribute of the solution obtained in step 10 is in the Tabu list. If yes, go to step 12, or else $S_{current} = S_{neighbor_best}$ and go to step 13.
- Step 12: Accept $S_{neighbor_best}$ if it has a better aspiration level than f_{best} and set $S_{current} = S_{neighbor_best}$, or else select a next-best solution that is not in the Tabu list to become the current solution.
- Step 13: Update the Tabu list and set $m=m+1$.
- Step 14: Repeat steps 7 to 13 until a specified maximum iteration has been reached.
- Step 15: Report the optimal solution.

8. Case study

The test system for the case study is a radial distribution system with 69 buses, 7 laterals and 5 tie-lines (looping branches), as shown in Fig. 11. The current carrying capacity of branch No.1-9 is 400 A, No. 46-49 and No. 52-64 are 300 A and the other remaining branches including the tie lines are 200 A. Four DG units are located at buses 14, 35, 46,

and 53 with capacities of 300, 200, 100, and 400 kW, respectively. The base values for voltage and power are 12.66 kV and 100 MVA. Each branch in the system has a sectionalizing switch for reconfiguration purpose. The load data are given in Table 1 and Table 2 provides branch data (Savier & Das, 2007). The initial statuses of all the sectionalizing switches (switches No. 1-68) are closed while all the tie-switches (switch No. 69-73) open. The total loads for this test system are 3,801.89 kW and 2,694.10 kVAr. The minimum and maximum voltages are set at 0.95 and 1.05 p.u. The maximum iteration for the Tabu search algorithm is 100. The fuzzy parameters associated with the three objectives are given in Table 3.

| Bus Number | P _L (kW) | Q _L (kVAr) | Bus Number | P _L (kW) | Q _L (kVAr) |
|------------|---------------------|-----------------------|------------|---------------------|-----------------------|
| 6 | 2.60 | 2.20 | 37 | 26.00 | 18.55 |
| 7 | 40.40 | 30.00 | 39 | 24.00 | 17.00 |
| 8 | 75.00 | 54.00 | 40 | 24.00 | 17.00 |
| 9 | 30.00 | 22.00 | 41 | 1.20 | 1.00 |
| 10 | 28.00 | 19.00 | 43 | 6.00 | 4.30 |
| 11 | 145.00 | 104.00 | 45 | 39.22 | 26.30 |
| 12 | 145.00 | 104.00 | 46 | 39.22 | 26.30 |
| 13 | 8.00 | 5.00 | 48 | 79.00 | 56.40 |
| 14 | 8.00 | 5.50 | 49 | 384.70 | 274.50 |
| 16 | 45.50 | 30.00 | 50 | 384.70 | 274.50 |
| 17 | 60.00 | 35.00 | 51 | 40.50 | 28.30 |
| 18 | 60.00 | 35.00 | 52 | 3.60 | 2.70 |
| 20 | 1.00 | 0.60 | 53 | 4.35 | 3.50 |
| 21 | 114.00 | 81.00 | 54 | 26.40 | 19.00 |
| 22 | 5.00 | 3.50 | 55 | 24.00 | 17.20 |
| 24 | 28.00 | 20.00 | 59 | 100.00 | 72.00 |
| 26 | 14.00 | 10.00 | 61 | 1,244.00 | 888.00 |
| 27 | 14.00 | 10.00 | 62 | 32.00 | 23.00 |
| 28 | 26.00 | 18.60 | 64 | 227.00 | 162.00 |
| 29 | 26.00 | 18.60 | 65 | 59.00 | 42.00 |
| 33 | 14.00 | 10.00 | 66 | 18.00 | 13.00 |
| 34 | 19.50 | 14.00 | 67 | 18.00 | 13.00 |
| 35 | 6.00 | 4.00 | 68 | 28.00 | 20.00 |
| 36 | 26.00 | 18.55 | 69 | 28.00 | 20.00 |

Table 1. Load data of 69-bus distribution system

| Branch Number | Sending end bus | Receiving end bus | R (Ω) | X (Ω) |
|---------------|-----------------|-------------------|--------|--------|
| 1 | 1 | 2 | 0.0005 | 0.0012 |
| 2 | 2 | 3 | 0.0005 | 0.0012 |
| 3 | 3 | 4 | 0.0015 | 0.0036 |
| 4 | 4 | 5 | 0.0251 | 0.0294 |
| 5 | 5 | 6 | 0.3660 | 0.1864 |
| 6 | 6 | 7 | 0.3811 | 0.1941 |
| 7 | 7 | 8 | 0.0922 | 0.0470 |
| 8 | 8 | 9 | 0.0493 | 0.0251 |
| 9 | 9 | 10 | 0.8190 | 0.2707 |
| 10 | 10 | 11 | 0.1872 | 0.0619 |
| 11 | 11 | 12 | 0.7114 | 0.2351 |
| 12 | 12 | 13 | 1.0300 | 0.3400 |
| 13 | 13 | 14 | 1.0440 | 0.3450 |
| 14 | 14 | 15 | 1.0580 | 0.3496 |
| 15 | 15 | 16 | 0.1966 | 0.0650 |
| 16 | 16 | 17 | 0.3744 | 0.1238 |
| 17 | 17 | 18 | 0.0047 | 0.0016 |
| 18 | 18 | 19 | 0.3276 | 0.1083 |
| 19 | 19 | 20 | 0.2106 | 0.0690 |
| 20 | 20 | 21 | 0.3416 | 0.1129 |
| 21 | 21 | 22 | 0.0140 | 0.0046 |
| 22 | 22 | 23 | 0.1591 | 0.0526 |
| 23 | 23 | 24 | 0.3463 | 0.1145 |
| 24 | 24 | 25 | 0.7488 | 0.2475 |
| 25 | 25 | 26 | 0.3089 | 0.1021 |
| 26 | 26 | 27 | 0.1732 | 0.0572 |
| 27 | 3 | 28 | 0.0044 | 0.0108 |
| 28 | 28 | 29 | 0.0640 | 0.1565 |
| 29 | 29 | 30 | 0.3978 | 0.1315 |
| 30 | 30 | 31 | 0.0702 | 0.0232 |
| 31 | 31 | 32 | 0.3510 | 0.1160 |
| 32 | 32 | 33 | 0.8390 | 0.2816 |
| 33 | 33 | 34 | 1.7080 | 0.5646 |
| 34 | 34 | 35 | 1.4740 | 0.4873 |
| 35 | 3 | 36 | 0.0044 | 0.0108 |
| 36 | 36 | 37 | 0.0640 | 0.1565 |
| 37 | 37 | 38 | 0.1053 | 0.1230 |

| | | | | |
|----------|----|----|--------|--------|
| 38 | 38 | 39 | 0.0304 | 0.0355 |
| 39 | 39 | 40 | 0.0018 | 0.0021 |
| 40 | 40 | 41 | 0.7283 | 0.8509 |
| 41 | 41 | 42 | 0.3100 | 0.3623 |
| 42 | 42 | 43 | 0.0410 | 0.0478 |
| 43 | 43 | 44 | 0.0092 | 0.0116 |
| 44 | 44 | 45 | 0.1089 | 0.1373 |
| 45 | 45 | 46 | 0.0009 | 0.0012 |
| 46 | 4 | 47 | 0.0034 | 0.0084 |
| 47 | 47 | 48 | 0.0851 | 0.2083 |
| 48 | 48 | 49 | 0.2898 | 0.7091 |
| 49 | 49 | 50 | 0.0822 | 0.2011 |
| 50 | 8 | 51 | 0.0928 | 0.0473 |
| 51 | 51 | 52 | 0.3319 | 0.1114 |
| 52 | 9 | 53 | 0.1740 | 0.0886 |
| 53 | 53 | 54 | 0.2030 | 0.1034 |
| 54 | 54 | 55 | 0.2842 | 0.1447 |
| 55 | 55 | 56 | 0.2813 | 0.1433 |
| 56 | 56 | 57 | 1.5900 | 0.5337 |
| 57 | 57 | 58 | 0.7837 | 0.2630 |
| 58 | 58 | 59 | 0.3042 | 0.1006 |
| 59 | 59 | 60 | 0.3861 | 0.1172 |
| 60 | 60 | 61 | 0.5075 | 0.2585 |
| 61 | 61 | 62 | 0.0974 | 0.0496 |
| 62 | 62 | 63 | 0.1450 | 0.0738 |
| 63 | 63 | 64 | 0.7105 | 0.3619 |
| 64 | 64 | 65 | 1.0410 | 0.5302 |
| 65 | 11 | 66 | 0.2012 | 0.0611 |
| 66 | 66 | 67 | 0.0047 | 0.0014 |
| 67 | 12 | 68 | 0.7394 | 0.2444 |
| 68 | 68 | 69 | 0.0047 | 0.0016 |
| Tie line | | | | |
| 69 | 11 | 43 | 0.5000 | 0.5000 |
| 70 | 13 | 21 | 0.5000 | 0.5000 |
| 71 | 15 | 46 | 1.0000 | 0.5000 |
| 72 | 50 | 59 | 2.0000 | 1.0000 |
| 73 | 27 | 65 | 1.0000 | 0.5000 |

Table 2. Branch data of 69-bus distribution system

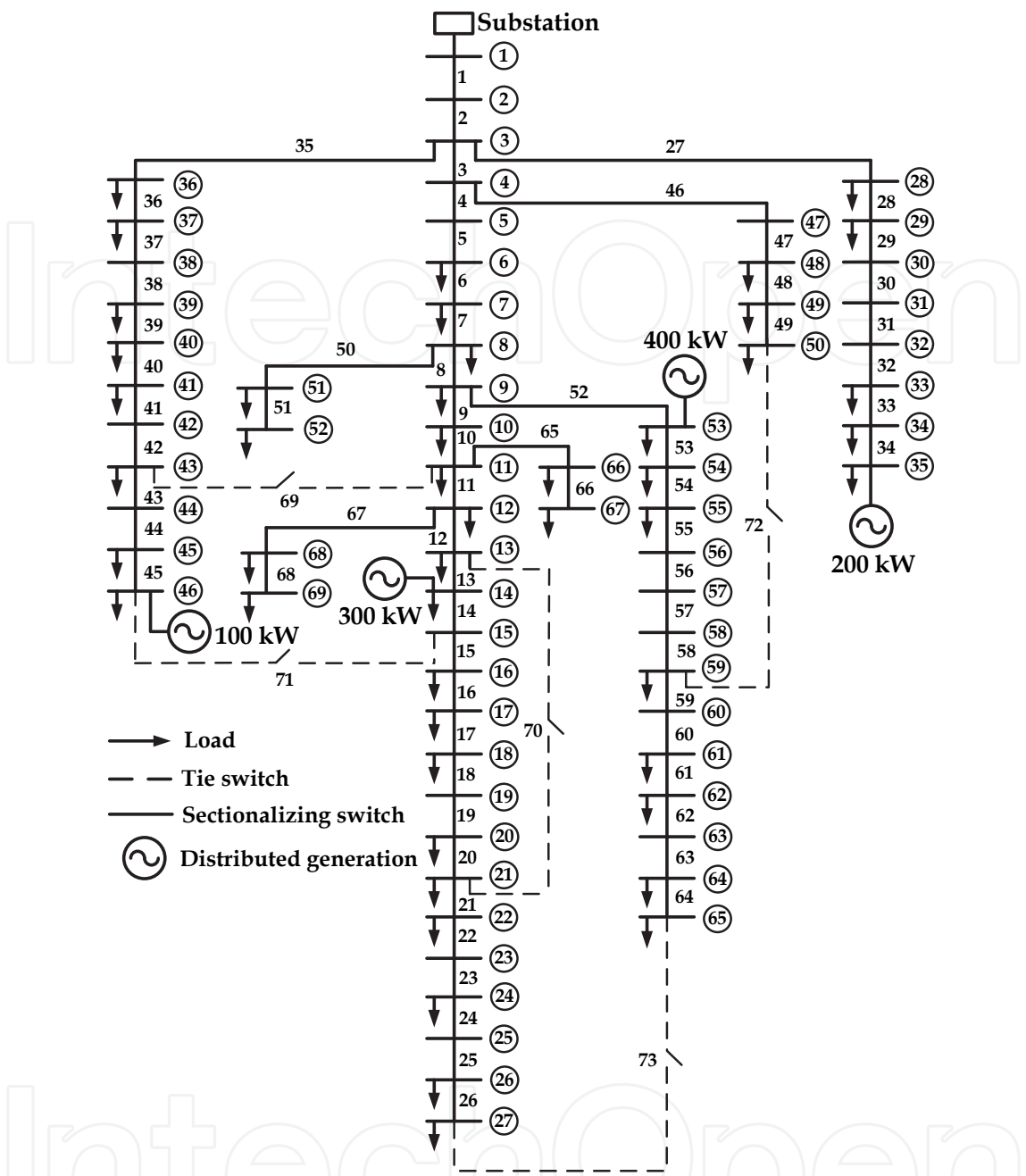


Fig. 11. Single-line diagram of 69-bus distribution system with distributed generation

- Six cases are examined as follows:
- Case 1: The system is without feeder reconfiguration
 - Case 2: The system is reconfigured so that the system power loss is minimized.
 - Case 3: The system is reconfigured so that the load balancing index is minimized.
 - Case 4: The same as case 2 with a constraint that the number of switching operations of sectionalizing and ties switches must not exceed 4.
 - Case 5: The system is reconfigured using the solution algorithm described in Section 4.
 - Case 6: The same as case 5 with system 20% unbalanced loading, indicating that the load of phase b is 20% higher than that of phase a but lower than that in phase c by the same amount.

| Fuzzy parameters | Value |
|------------------|-------|
| PL_{min} | 0.5 |
| PL_{max} | 1.0 |
| LB_{min} | 0.7 |
| LB_{max} | 1.0 |
| SW_{min} | 4.0 |
| SW_{max} | 10 |

Table 3. Fuzzy parameters for each objective

The numerical results for the six cases are summarized in Table 4. In cases 1-5 (balanced systems), the system power loss and the LBI are highest, and the minimum bus voltage in the system violates the lower limit of 0.95 per unit. The voltage profile of case 1 is shown in Fig. 12. It is observed that the voltages at buses 57-65 are below 0.95 p.u. because a large load of 1,244 kW are drawn at bus 61. Without the four DG units, the system loss would be 673.89 kW. This confirms that DG units can normally, although not necessarily, help reduce current flow in the feeders and hence contributes to power loss reduction, mainly because they are usually placed near the load being supplied. In cases 2 to 5, where the feeders are reconfigured and the voltage constraint is imposed in the optimization process, no bus voltage is found violated (see Figs.12 and 13).

| | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 | Case 6 |
|------------------------------------|--------|----------------|--------------------|--------|------------|------------|
| Sectionalizing switches to be open | - | 12, 20, 52, 61 | 42, 14, 20, 52, 61 | 52, 62 | 13, 52, 63 | 12, 52 61 |
| Tie switches to be closed | - | 70, 71, 72, 73 | 69, 70, 71, 72, 73 | 72, 73 | 71, 72, 73 | 71, 72, 73 |
| Power loss (kW) | 586.83 | 246.33 | 270.81 | 302.37 | 248.40 | 290.98 |
| Minimum voltage (p.u.) | 0.914 | 0.954 | 0.954 | 0.953 | 0.953 | 0.965 |
| Load balancing index (LBI) | 2.365 | 1.801 | 1.748 | 1.921 | 1.870 | 2.273 |
| Number of switching operations | - | 8 | 10 | 4 | 6 | 6 |

Table 4. Results of case study

As expected, the system power loss is at minimum in case 2, the LBI index is at minimum in case 3, and the number of switching operations of switches is at minimum in case 4. It is obviously seen from case 5 that a fuzzy multiobjective optimization offers some flexibility that could be exploited for additional trade-off between improving one objective function and degrading the others. For example, the power loss in case 5 is slightly higher than in case 2 but case 5 needs only 6, instead of 8, switching operations. Although the LBI of case 3 is better than that of case 5, the power loss and number of switching operations of case 3 are greater. Comparing case 4 with case 5, a power loss of about 18 kW can be saved from two more switching operations. It can be concluded that the fuzzy model has a potential for solving the decision making problem in feeder reconfiguration and offers decision makers some flexibility to incorporate their own judgment and priority in the optimization model.

The membership value of case 5 for power loss is 0.961, for load balancing index is 0.697 and for number of switching operations is 0.666.

When the system unbalanced loading is 20% in case 6, the power loss before feeder reconfiguration is about 624.962 kW. The membership value of case 6 for power loss is 0.840, for load balancing index is 0.129 and for the number of switching operations is 0.666. The voltage profile of case 6 is shown in Fig. 14.

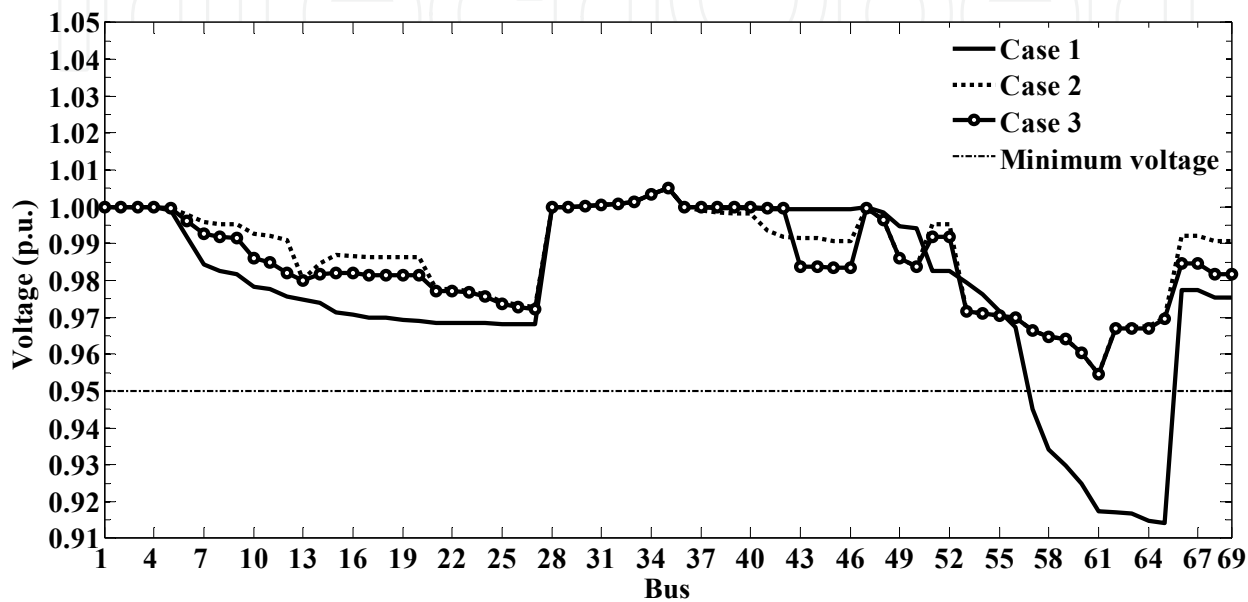


Fig. 12. Bus voltage profile in cases 1, 2 and 3

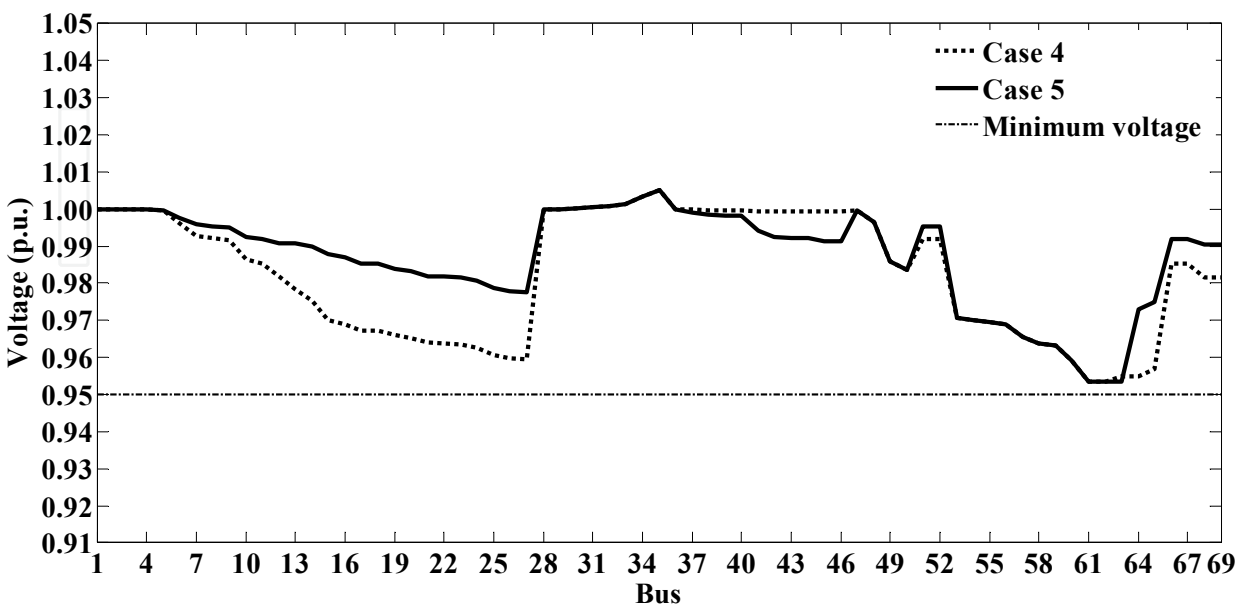


Fig. 13. Bus voltage profile in cases 4 and 5

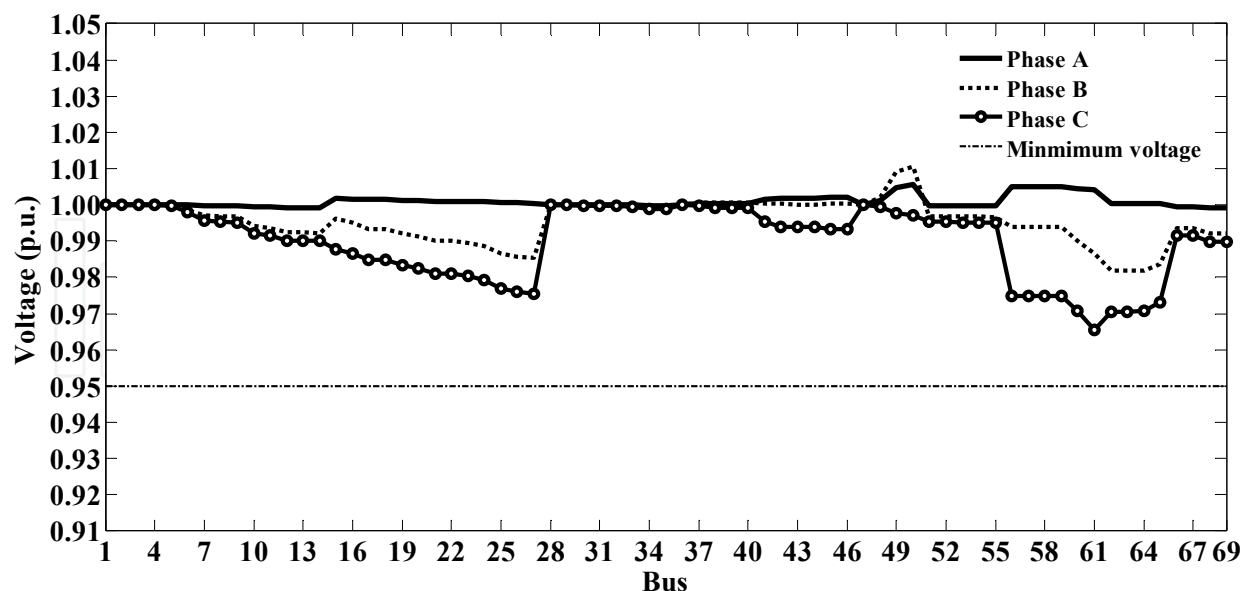


Fig. 14. Bus voltage profile in cases 6

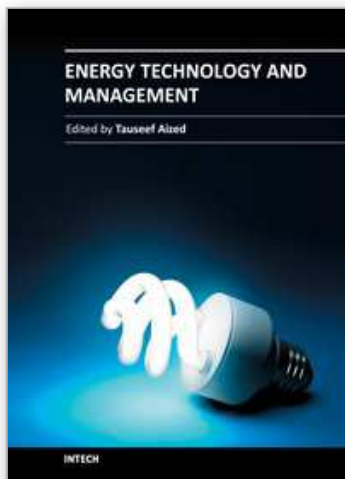
9. Conclusion

A fuzzy multiobjective algorithm has been presented to solve the feeder reconfiguration problem in a distribution system with distributed generators. The algorithm attempts to maximize the satisfaction level of the minimization of membership values of three objectives: system power loss, load balancing index, and number of switching operations for tie and sectionalizing switches. These three objectives are modeled by a trapezoidal membership function. The search for the best compromise among the objectives is achieved by Tabu search. On the basis of the simulation results obtained, the satisfaction level of one objective can be improved at the expense of that of the others. The decision maker can prioritize his or her own objective by adjusting some of the fuzzy parameters in the feeder reconfiguration problem.

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